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A Multi-parameter Approach to Automated Building Grouping and Generalization

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Abstract This paper presents an approach to automated building grouping and generalization. Three principles of Gestalt theories, i.e. proximity, similarity, and common directions, are employed as guidelines, and six parameters, i.e. minimum distance, area of visible scope, area ratio, edge number ratio, smallest minimum bounding rectangle (SMBR), directional Voronoi diagram (DVD), are selected to describe spatial patterns, distributions and relations of buildings. Based on these principles and parameters, an approach to building grouping and generalization is developed. First, buildings are triangulated based on Delaunay triangulation rules, by which topological adjacency relations between buildings are obtained and the six parameters are calculated and recorded. Every two topologically adjacent buildings form a potential group. Three criteria from previous experience and Gestalt principles are employed to tell whether a 2-building group is 'strong,' 'average' or 'weak.' The 'weak' groups are deleted from the group array. Secondly, the retained groups with common buildings are organized to form intermediate groups according to their relations. After this step, the intermediate groups with common buildings are aggregated or separated and the final groups are formed. Finally, appropriate operators/algorithms are selected for each group and the generalized buildings are achieved. This approach is fully automatic. As our experiments show, it can be used primarily in the generalization of buildings arranged in blocks.

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1 Introduction

Map generalization is a procedure for solving spatial conflicts and congestions in the process of generating smaller scale maps from larger scale ones using various appropriate operations (e.g. selection, displacement, simplification of map objects) under definite conditions (e.g. map scale, purpose, etc.). The construction of spatial data infrastructures (SDI) in many nations and regions and the widespread use of geographic information in computers in the context of geographic information systems (GIS) have brought with them the demand for automation of map generalization [8]. Indeed, automated map generalization has become an indispensable component and a hot issue in cartography and the GIS community in recent years [9], [10], [18].

This paper focuses on automated building generalization in city blocks, with a focus on the step of detecting and forming meaningful building groups, preceding the actual generalization phase. Contextual features, such as roads and rivers, are not considered in our approach. To date, several methods for building grouping and generalization have been proposed. The approach for object grouping proposed by Steinhauer et al. [20] uses the adjacency of buildings in the Voronoi diagram, the distance between buildings, and their cardinality as criteria to form building groups. The method was designed as a generic procedure for the recognition of so-called abstract regions in cartographic maps, consisting of disjoint map objects of arbitrary type (and not just buildings). Hence, while the use of the Vononoi diagram for that purpose is elegant and while the procedure offers the potential for the detection of arbitrary object groups the approach also ignores the use of grouping criteria that are more specific and important to buildings, such as directional or size relations among buildings. Christophe and Ruas [4] also present an approach to building grouping, yet one that focuses on the detection of a very special kind of groups, that is, buildings aligned in rows. Regnauld [15] shows how such aligned groups of buildings can be generalized by so-called typification, reducing the number of buildings in the generalization process, while maintaining the general pattern of the alignment. Boffet and Rocca Serra [3] present measures that can be used to characterize urban blocks and thw objects contained therein (incl. buildings). Their main interest is on the urban block as a whole, with the aim of classifying different types of settlement patterns. Their main contribution is the proposal of a series of measures to characterize the ‘free space’ between buildings. Rainsford and Mackaness [14] concentrate on the simplification of the shape of individual buildings by means of template matching. Common to all methods discussed above is that they tend to focus on particular aspects of building groups or individual buildings only. For instance, directional relations among buildings have rarely been taken into consideration, and if so then only for special cases (e.g. [4] for the detection of building alignments). For this reason, our intention is to propose a new, more comprehensive approach, integrating directional relations with several other parameters.

Buildings are generally symbolized as discretely distributed rectangular polygons on large-scale and intermediate-scale maps. With the reduction of map scale, the maps become crowded and illegible. Hence, many buildings need to be deleted, merged, collapsed, or simplified, and so on. According to observations in the literature [20] and our experience in manual generalization, cartographers usually divide buildings into groups before generalization and then perform different operations on different building groups. Further analyzing and decomposing this process, it can be found that trained cartographers generally perform the following three successive steps in the process of building generalization:

(1) A description of patterns and relations of buildings appears in cartographers' mind (mental map);
(2) Buildings are clustered into groups; and
(3) Appropriate operations are selected to perform the actual generalization process.

Computer-aided map generalization is an imitation of cartographers' behaviors. Hence, for the purpose of automated building generalization, the following three questions naturally arise:

(1) How can a good description of the patterns, structures and relations of buildings be achieved?
(2) How can buildings be combined into groups?
(3) How can building groups be matched to appropriate generalization operations.

This research aims at answering the three questions. We clearly place our emphasis on questions (1) and (2), while question (3) is only partially addressed.

To facilitate discussion, the procedure for separating buildings into groups is called 'building grouping' in this paper.

The remainder of this paper is organized as follows: Section 2 presents, based on Gestalt theory, three rules that should be obeyed in building grouping and six parameters used to describe the structures, patterns and relations of buildings. Then, an approach to building grouping (Section 3) and generalization (Section 4) are addressed in detail. These two sections comprise the main parts of the work. To test the approach, two examples are given in Section 5. The validity of the approach is discussed in Section 6. Finally, some conclusions are made (Section 7).

2 Parameters for building grouping and generalization

2.1 Rules for building grouping

At least eight Gestalt principles [11], [16] have so far been adopted in automated map generalization to form groups of cartographic objects (e.g. [2], [22], [24]. They may be defined as follows:

- Proximity: Objects at close distance have a tendency to be perceived as a group (Fig. 1a).

(a) (b) (c)

Fig. 1 Examples of rules for building grouping (buildings in dotted rectangle*s* form a group). **a** Proximity: two close buildings form a group, while the distant one is separated. **b** Similarity: although the distances between pairs of buildings are equal, only the two buildings of same size and shape form a group. **c** Common direction: in case that distances, shapes and sizes are similar, only those objects that are arranged in the same directions form a group

- Similarity: Objects of similar shape and size perceptually form a group (Fig. 1b).
- Common orientations/directions: Objects arranged in a similar direction are perceived as a group (Fig. 1c).
- Continuity: Regularities or tendencies persist and are not easily disturbed. For example, two crossed curves maintain their respective continuity.
- Connectedness: Connected elements can easily form a group.
- Closure: An object group with a closed tendency is easily regarded as being perceptually closed.
- Common fate: The objects that are moving in the same direction appear to be grouped together (It is used in dynamic maps).
- Common region: Objects in the same region are more easily grouped together.

As far as map buildings within the scope of a specific street block are concerned, continuity, connectedness and closure imply that distances are zero. Hence, they can be substituted by proximity. The principle of common region is context-related, meaning that buildings in super-blocks are partitioned by streets and rivers, and are beyond the scope of this research which is restricted to buildings contained in street blocks. The principle of common fate is only relevant in dynamic maps. Therefore, only the first three of the above principles, that is, proximity, similarity and common direction, are taken into consideration for building grouping in this research (as illustrated in Fig. 1).

2.2 Parameters for describing relations and patterns of buildings

Previous work [3], [9], [15] suggests that six parameters and their thresholds are particularly suited to describe buildings in light of building grouping. These are:

(1) *Minimum distance*: The minimum distance between two buildings.

(2) *Area of visible scope*: A detailed explanation of definition of visible scopes is presented later in this section while discussing directional relations.

(3) *Similar size*: The area ratio is generally used to evaluate size similarity between two buildings P and Q.

$$R_a^{P,Q} = \frac{A_{\min}}{A_{\max}} \tag{1}$$

Where $R_a^{P,Q}$ is the area ratio of P and Q, and $A_{\max}$ is the area of the larger building, and Amin is the area of the smaller building.

(4) *Similar shape*: The edge number ratio may be used to evaluate shape similarity between two buildings P and Q.

$$R_s^{P,Q} = \frac{E_{\min}}{E_{\max}} \tag{2}$$

Where $R_s^{P,Q}$ is the ratio of the number of edges of P and Q, and $E_{\min}$ is the number of edges of the building with fewer edges, and $E_{\max}$ is the number of edges of the building with more edges.

Using this function for the description of shape similarity between buildings is based on the fact that the internal angles of most buildings on maps are orthogonal. Hence, it can work well in most cases.

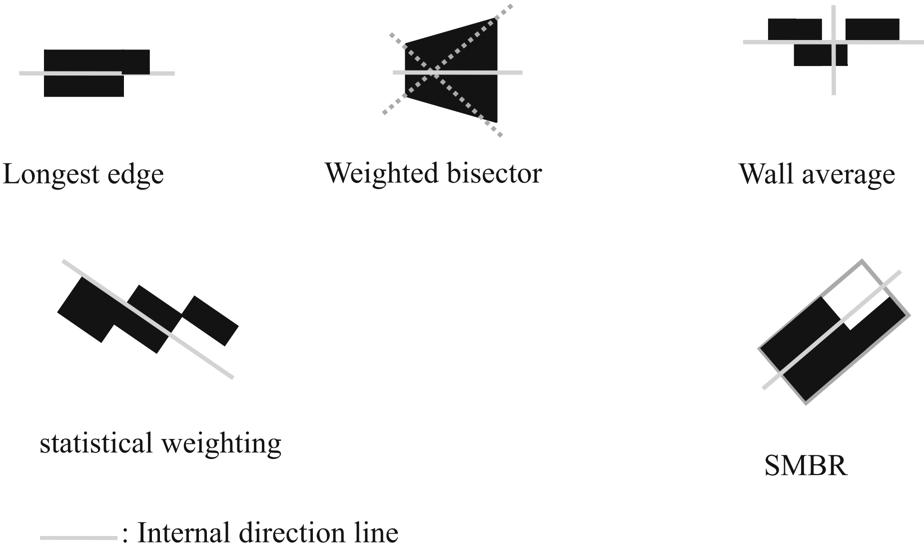


Fig. 2 Five measures for describing internal directions, as proposed by Duchêne et al. [5]

(5) *Internal orientation/direction*

Internal orientation can be used to describe the spatial extent of an individual building. Duchêne et al. [5] summarized five measures (Fig. 2), including ‘longest edge,’ ‘weighted bisector,’ ‘wall average,’ ‘statistical weighting,’ and ‘smallest minimum bounding rectangle (SMBR),’ and concluded from their experiments that the SMBR is the most appropriate one.

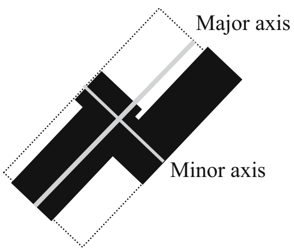
To use the SMBR efficiently in building grouping, the major axis and minor axis are defined (as shown in Fig. 3) to denote the two main extents of a building. Major axes are more often used, however minor axes also may take an effect, especially if the directional extent of a building is not perceptually clear, that is, if the lengths of the major axis and minor axis are similar.

(6) *Directions between objects*

The MBR model [12], [19], the cone model [13], the directional relation matrix model [6] and the direction Voronoi diagram (DVD) model [23] have been proposed for the description of direction relations. The DVD model is employed here. The DVD model describes directional relations of two objects using DVDs. The procedure for the calculation of DVDs is as follows.

Step 1 Calculate the visible scope between two buildings: If a line segment connecting two vertices of buildings *A* and *B* has no intersection point (except the vertices themselves) with *A* and *B* and any other buildings, *A* and

Fig. 3 Major axis and minor axis of an SMBR. Major axis: the longer axis of an SMBR. Minor axis: the shorter axis of an SMBR



B are defined as 'visible to each other' and the two vertices are defined as 'visible vertices.' A scope between A and B whose boundary consists of all of the visible vertices is defined as 'visible scope' of the two buildings. For example, in Fig. 4a, the visible scope of the two buildings is the polygon $P_2P_3P_4P_5P_8P_7P_2$.

Step 2 Triangulate the visible scope: Take all vertices of the visible scope as a point set in 2-dimensional space, and construct the Delaunay triangles [7]. Delete those triangles whose vertices belong to the same building.

Step 3 Compute DVDs: A curve may be formed by connecting the mid-points of each edge whose end-points belong to different buildings. The curve generally consists of several line segments. The normal line of each line segment denotes a direction, and the ratio of the length of the line segment with the total length of the curve is the weight (see a_1, a_2, ... a_8 in function (3)) of this direction. All normal lines and their corresponding weights form a direction group, which presents a quantitative description of directions of two buildings. For example, in Fig. 4a, the DVDs are composed of three line segments, which means three directions are needed for the description of direction relations of the two buildings.

Step 4 formation of directional group: In the eight-direction system [6], north means an azimuth (see Fig. 4b for the definition of azimuth) in $(337.5°, 0°] \cup (0°, 22.5°]$; northeast an azimuth in (22.5°,67.5°]; east an azimuth in (67.5°, 112.5°]; southeast an azimuth in (112.5°,157.5°]; south an azimuth in (157.5°, 202.5°]; southwest an azimuth in (202.5°,247.5°]; west an azimuth in (247.5°,292.5°]; northwest an azimuth in (292.5°,337.5°]. While putting each azimuth into a cardinal direction, the corresponding weights belonging to same cardinal direction are also added up, so that a quantitative description of directional relations of two buildings (say, P and Q) can be expressed by function (3).

$$Dir(P,Q) = \{< N, a_1 >, < NW, a_2 >, < W, a_3 >, ..., < NE, a_8 >\} \quad (3)$$

Where a_i (i=1,2,......,8) is a weight and $\sum_{i=1}^{8} a_i = 1$; N, NW, ..., and NE are cardinal directions.

If $Dir(Q,O) = \{< N, b_1 >, < NW, b_2 >, < W, b_3 >, ..., < NE, b_8 >\}$, the common directions of buildings P Q, and O can be expressed by function (4).

$$Dir(P,Q) \cap Dir(Q,O) = \{< N, a_1 \vee b_1 >, < NW, a_2 \vee b_2 >, ..., < NE, a_8 \vee b_8 >\} \quad (4)$$

To facilitate the discussion, $a_i^{P,Q,O} = a_i \vee b_i$ is used to denote the weight of a common cardinal direction of objects P Q, and O.

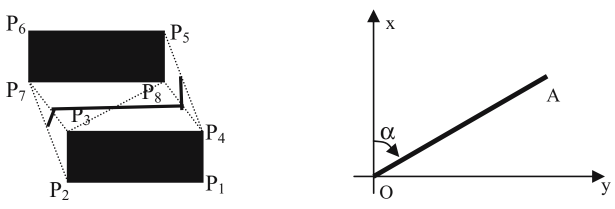


Fig. 4 Principles of the DVD model. **a** The thick line segments between the two objects are DVDs; **b** the definition of azimuths

3 Building grouping

To cluster buildings of a given street block into groups for the purpose of generalization, we can use an iterative approach to form small, potential building groups first, and then combine them into intermediate groups, and eventually obtain the final groups appropriate for the target scale. This strategy is employed in our approach; therefore the following three processes are discussed in this section:

(1) Topological adjacency (or proximity) relations are detected, so that all 2-building groups are obtained.
(2) Intermediate groups are constructed according to spatial relations of 2-building groups.
(3) The intermediate groups with common buildings are either separated or aggregated, so that the final groups are achieved.

3.1 Detection of potential 2-building groups

This process consists of three steps.

(1) *Triangulation of the buildings*: Construct the Delaunay triangulation [7] between buildings using all vertices of the two objects, forming three types of triangles (Fig. 5a). If three points of a triangle belong to the same building and the triangle is located in the building, this triangle is called a 'building triangle.' 'True connection triangles' link two or three different buildings like a bridge. 'False connection triangles'

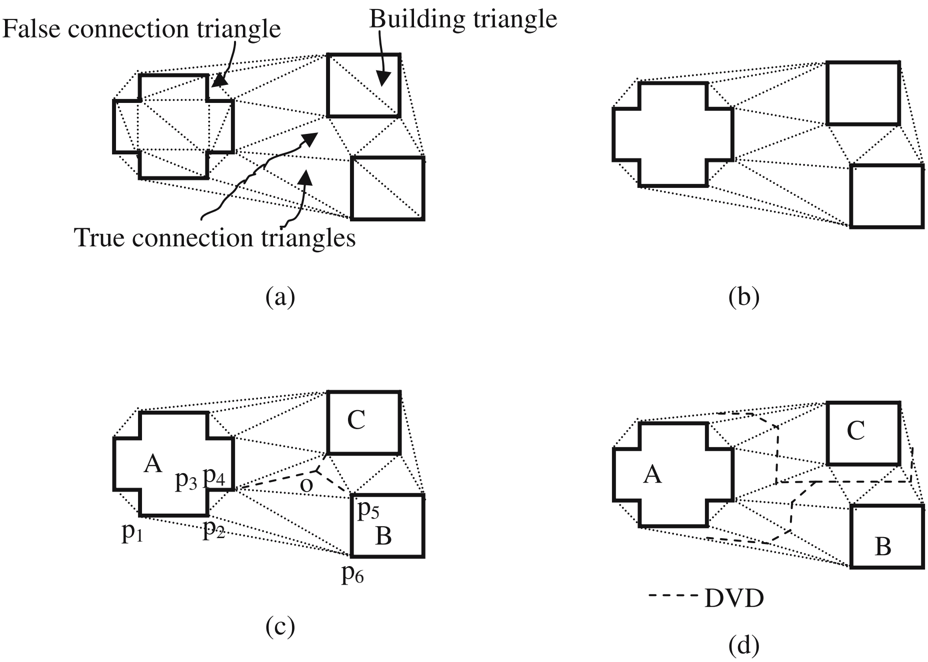


Fig. 5 Detection of topological adjacency relations and calculation of associated parameters. **a** Taking all vertices of the buildings as point set, the space is triangulated using the Delaunay triangulation rules; **b** building triangles are deleted from the triangle array; **c** visible scopes between every two adjacent buildings are constructed; and **d** the triangle array is traced and the DVDs of every two adjacent buildings are generated

are those that link the concave parts of a building. To detect topologically adjacent buildings, only the connection triangles are necessary. Hence, the building triangles are deleted from the triangle array, and only connection triangles are retained (Fig. 5b).

(2) *Detection of adjacency relations*: In connection triangles, if three vertices of the triangle belong to the same building, this triangle is called a 'false connect triangle' (it is generally at a concave part of the polygon). Otherwise it is called a 'true connection triangle' (Fig. 5a). If a vertex of a true connection triangle belongs to a building, this triangle belongs to the building. Hence, every true connection triangle belongs to (and connects) two or three buildings. Two buildings owning a common triangle are defined as topologically adjacent, also implying a proximity relation.

(3) *Calculation of the parameters*: The calculation of the parameters proposed in Section 2.2 is only carried out between two topologically adjacent buildings. Because it is easy to calculate area ratios, edge number ratios and SMBRs, we only discuss the calculation of the other three parameters here.

- *Minimum distance*: In the scope of every true connection triangle of two buildings, there must be a minimum distance between the two buildings. It is obvious that the minimum one of these distances in the scopes of true connection triangles is the minimum distance of the two buildings.
- *Area of visible scope*: The definition of the visible scope of two buildings has been discussed in Section 2.2. However, the number of buildings is generally more than two in a block. In this case, there must be at least one triangle that belongs to three buildings. Hence, the problem of partitioning such connection triangles needs to be considered carefully. Here, for each such triangle, three line segments, each formed by connecting a vertex and the intersection point of the bisectors (i.e. the centroid), are constructed to partition the triangle. Take Fig. 5c as an example. The centroid of the triangle belonging to buildings *A*, *B* and *C* is o, so the visible scope of *A* and *B* is polygon $p_1p_2p_3p_4op_5p_6$. A simple method for the calculation of the area of a visible scope is to sum up the areas of all triangles in the visible scope.
- *DVD*: In order to obtain the direction Voronoi diagram, the connection triangle array is searched to detect all true connection triangles. Using the methods introduced in Section 2.2, DVDs between each pair of adjacent objects can be obtained (Fig. 5d). Then, the directions and their weights can be computed using the DVDs.

To save the above parameters, a structure named Parameter-Saver is defined as follows based on C^{++} (because the approach in this paper has been realized by the authors in C^{++}), and a $k \times k$ matrix (say T) whose data type is Parameter-Saver is constructed to record the parameters of every two topologically adjacent buildings, where k is the number of buildings.

```
Typedef struct TagParameter-Saver{

BOOL isAdjacent              //if two buildings are topologically adjacent
float MinDistance;           //minimum distance
float VisibleArea;           //area of visible scope
float AreaRatio;             //area ratio
float ENumRatio;             //edge number ratio
float MajorAxis;             //major axis of SMBR
float MinAxis;               //minor axis of SMBR
float Drelation [8];         //weights of directional relations in 8-direction system
} Parameter-Saver
```

(4) *Formation of 2-building groups*: Using the parameters recorded in matrix *T*, it is easy to obtain all potential 2-building groups, each of which is composed of two topologically adjacent buildings, denoted by the values of 'isAdjacent' in Parameter-Saver. An example for the construction of 2-building groups is shown in Fig. 6a and will be discussed further in the following section.

3.2 Construction of intermediate building groups

To combine two 2-building groups, it is necessary to know: (1) the characteristics of the two groups themselves, and (2) the relations between the two groups. The latter can be described using the parameters minimum distance and area of visible scope. For the former, a parameter named 'compactness' for evaluating whether a building group is 'strong,' 'average' or 'weak' is defined. Here, three rules are employed, based on experience [9], [24] and the three Gestalt principles selected in Section 2, to evaluate the compactness of a 2-building group (say, *G*):

(1) If $D>D_{\text{limit}}$ and $A>A_{\text{limit}}$, *G* is a weak group;
(2) If $D>D_{\text{limit}}$ and $A\leq A_{\text{limit}}$, or $D\leq D_{\text{limit}}$ and $A>A_{\text{limit}}$, *G* is an average group; and
(3) If $D\leq D_{\text{limit}}$ and $A\leq A_{\text{limit}}$, *G* is a strong group.

Here, the following definitions are used:

D_{limit} 0.2 mm is separation threshold in map space [21];
A_{limit} 0.4 mm×0.5 mm is area threshold in map space [21];
D minimum distance between two buildings; and
A area of visible scope between two buildings.

In general, for a group of *n* buildings ($n\geq 3$), if *D* is substituted by $\overline{D}$ (mean minimum distance) and *A* is substituted by $\overline{A}$ (mean area of visible scopes), the above three rules can be also used to evaluate the compactness of intermediate groups.

Weak groups are subsequently deleted; while strong and average ones are retained (such an example is shown in Fig. 6b).

These retained groups cannot yet be directly generalized, for they are too segmented and have the potential to be aggregated to intermediate groups. Therefore, a further combination of these small groups is necessary. Suppose that two groups $G_1=\{A_1, A_2, A_3,...A_n, B\}$ and $G_2=\{B, C_1, C_2, C_3,...C_m\}$ exist. Here, B is the common building of the two intermediate groups (see Fig. 6). If one of the following criteria is satisfied, G_1 and G_2 can be aggregated into a bigger group *G*:

(1) Both G_1 and G_2 are strong groups.
(2) In case one group is strong and the other is average, it should have $R_a^{A_n,B}\geq 0.6$ and $R_s^{A_n,B}\geq 0.6$ and $R_a^{B,C_1}\geq 0.6$ and $R_s^{B,C_1}\geq 0.6$, or $a_i^{A,B,C}\geq 40\%$ and both of the acute angles, respectively, formed by the major axes of A_n and *B, B* and C_1, are less than 15°.
(3) In case both G_1 and G_2 are average groups, it should have $R_a^{A_n,B}\geq 0.6$ and $R_s^{A_n,B}\geq 0.6$ and $R_a^{B,C_1}\geq 0.6$ and $R_s^{B,C_1}\geq 0.6$, or $a_i^{A,B,C}\geq 40\%$, and both of the acute angles respectively, formed by the major axes of A_n and *B, B* and C_1, are less than 15°.

At the beginning, G_1 and G_2 are 2-building groups; after the first round of aggregation, some become 3-building groups, so the compactness of each new group and *D* and *A* between each pair of potentially will-be-aggregated groups are re-calculated, and the above

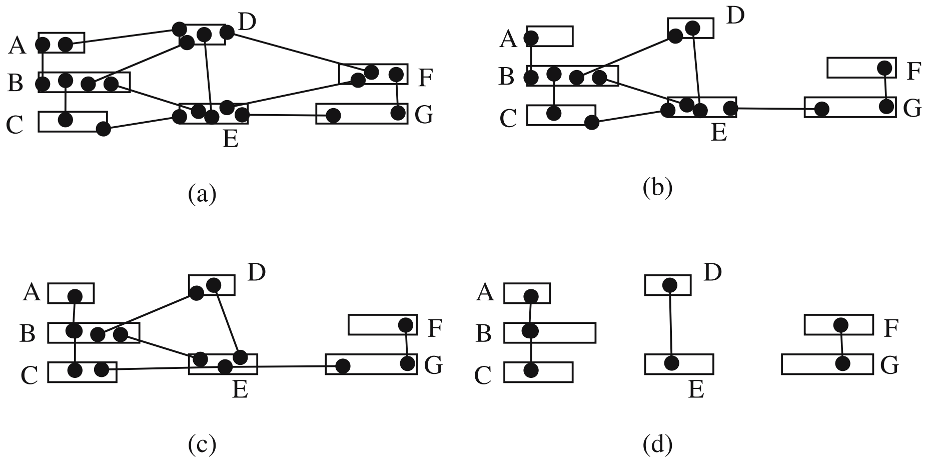


Fig. 6 Principles of building grouping. **a** Formation of 2-building groups (*a dot-ended line segment connection* denotes a 2-building group). **b** Deletion of weak groups (three connections between buildings *A* and *D, D* and *F, E* and *F* are removed). **c** Formation of intermediate groups, forming the six groups {*A, B, C*}, {*B, E*}, {*B, D*}, {*D, E*}, {*C, E, G*} and {*F, G*}. **d** Aggregation and separation of common buildings. Group {*A, B, C*} is stronger than groups {*B, D*} and {*B, E*}, and *D* and *E* belong to group {*D, E*} if it is separated from group {*A, B, C*}, thus building *B* only belongs to group {*A, B, C*}, that is, the connections between *B* and *D, B* and *E* are removed. Similarly, the connections between *C* and *E, E* and *G* are also removed and the buildings separated

three rules are re-carried out to aggregate them. This process is repeated until no groups can be aggregated.

Figure 6b and c together illustrate an example of the construction of intermediate groups.

3.3 Formation of final groups

After the above procedure, the intermediate groups cannot be generalized yet, for some buildings appear in two or more groups simultaneously (see Fig. 6c). For the purpose of directly performing generalization operations on every group, the groups owning common buildings need to be either separated or aggregated. Suppose that G_1 and G_2 are two groups and G_1 is stronger than G_2.

Here, the criterion for evaluating whether G_1 is stronger than G_2 is to compare the mean distance between buildings, the mean area of visible scopes between buildings, the mean value of common directions, the number of buildings, the mean value of area ratios, and the mean value of edge number ratios of the two groups in dictionary order. The greater the value is, the stronger the group.

The rules for aggregating and separating groups are:

(1) If no building in G_2, except the common building, exists in any other group, merge G_1 and G_2; otherwise,
(2) Delete the common building from G_2, i.e. the common building is only retained in the stronger group G_1.

After this step, the final groups that are ready to be generalized are achieved.

4 Generalization of buildings

To generalize the building groups, appropriate generalization operations must be selected for each specific group. Let G be a group that will be generalized and let N be the number of buildings in G. The following rules are used to select operations for G:

(1) If N=1 and the area of the building is less than 0.4 mm×0.5 mm in map space [21], the operations are 'collapse' (to centroid) and 'enlargement.'
(2) Otherwise, if N=1 and the area of the building is not less than 0.4 mm×0.5 mm in map space [21], the operation is 'boundary simplification.'
(3) Otherwise, if N=2, the operations are 'aggregation' and 'boundary simplification.'
(4) Otherwise, if $N \geq 3$, find adjacent groups of G. If the characteristics of the adjacent groups are similar to that of G, the operations are 'typification' (here, 'typification' means 'aggregation' + 'division') and 'boundary simplification.' Alternatively, compare the free space (say A_s) with the sum area of buildings (say A_b) in this group. If $A_b > A_s$ the operations are 'aggregation' and 'boundary simplification;' otherwise, the operations are 'selection' and 'boundary simplification.'
(5) Otherwise, the operations are 'aggregation' and 'boundary simplification.'

After all of the groups are generalized, the topological relations among generalized buildings need to be checked, since they may now overlap. For this purpose, generalized buildings are re-triangulated to detect their minimum distances. If two buildings overlap, a compromise method, slightly moving the buildings or slightly reducing the areas of buildings, is employed to settle this dilemma.

5 Experiments

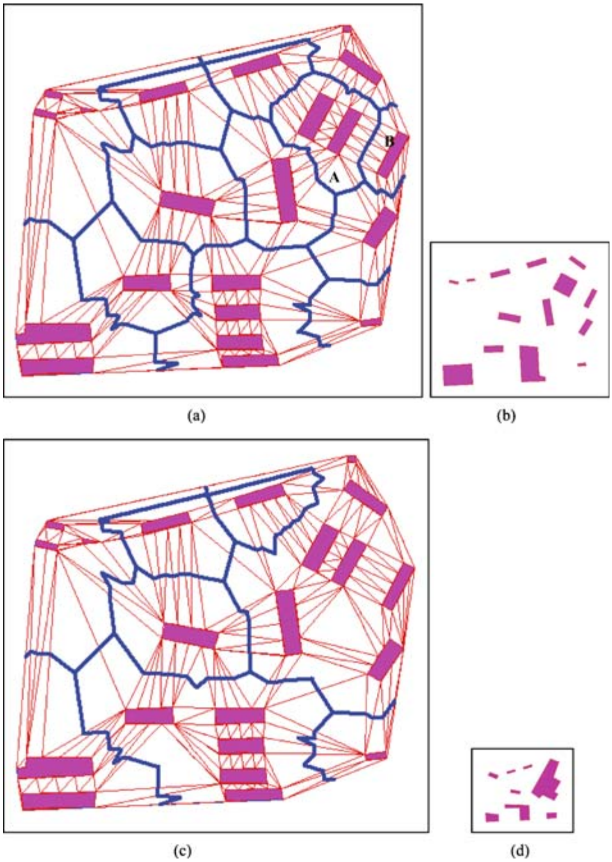
The proposed approach has been implemented in Visual C++ (Version 6.0) and integrated into a topographic map generalization system named Automap. The functions and the criteria used in the approach are empirical, therefore various experiments have been carried out by the authors to test the approach. Three of them are shown in Figs. 7, 8 and 9, respectively. Test data sets are provided by Shenzhen Municipal Bureau of Land Resource, Guangdong Province, China (see Figs. 7 and 8) and by the Institut G8.ographique National (IGN), France (see Fig. 9). Simulated data has also been used for particular purposes but is not shown here.

The three examples (illustrated in Figs. 7, 8 and 9) use topographic maps at the source scale of 1:10, 000 to generate maps at scales 1:25, 000 and 1:50, 000, respectively. To demonstrate the adaptability of the approach, different types of data have been chosen, representative of different shapes and arrangements of buildings:

- Experiment 1 (Fig. 7): Simple, mainly rectangular building shapes; parallelism between building groups but different orientations overall.
- Experiment 2 (Fig. 8): Non-convex building shapes, but still mainly orthogonal in the corners; different orientations with little parallelism.
- Experiment 3 (Fig. 9): Complex, non-convex building shapes with arbitrary corner angles; different orientations with little parallelism.

Delaunay triangulations and the separation lines of building groups (thick lines are used to separate groups) are depicted on the original maps, and the generalized maps are shown next to the original ones for comparison.

Fig. 7 Experiment 1 for building grouping and generalization (source map scale is 1:10,000): The buildings have simple and rectangular shapes, and have different orientations and much parallelism. **a** Grouping result for generating 1:25,000 map. **b** Generalized map at scale 1:25,000. **c** Grouping result for generating 1:50,000 map. **d** Generalized result at scale 1:50,000. All maps not shown to scale



6 Discussion

A number of insights can be gained from our experiments. Firstly, in building grouping, the principle of proximity takes priority over the other two principles. Hence, the parameters minimum distance and area of visible scope are prior to the other parameters. One such situation is shown in Fig. 7a: although three buildings in groups *A* and *B* are arranged in the same direction, the minimum distance and area of visible scope of the two buildings in group *A* are obviously less than that of the building in group *B* and the closest building in group *A*. Therefore, the two buildings with smaller minimum distance and smaller area of visible scope are clustered into one group. Group *C* in Fig. 8a shows a different kind of situation: the principles of similarity and of common direction almost can't work in this case, since the minimum distances are all less than the separation threshold and the areas of visible scope are all less than the area threshold, so they are directly clustered into a group based on the principle of proximity before the other two principles take effect.

The threshold values for D_{limit}=0.2 mm and A_{limit}=0.4 mm×0.5 mm are from SSC [21]; while the other ones (e.g. $a_i^{A,B,C} = 40\%$ for common directions, $R_a^{P,Q} = 0.6$ for similar area, $R_s^{P,Q} = 0.6$ for similar size) used in the criteria for aggregating small building groups (see Section 3.2) are based on previous experience and experiments [9], [23]. They appear to work well in most cases, but occasionally lead to unsatisfactory results when the calculated

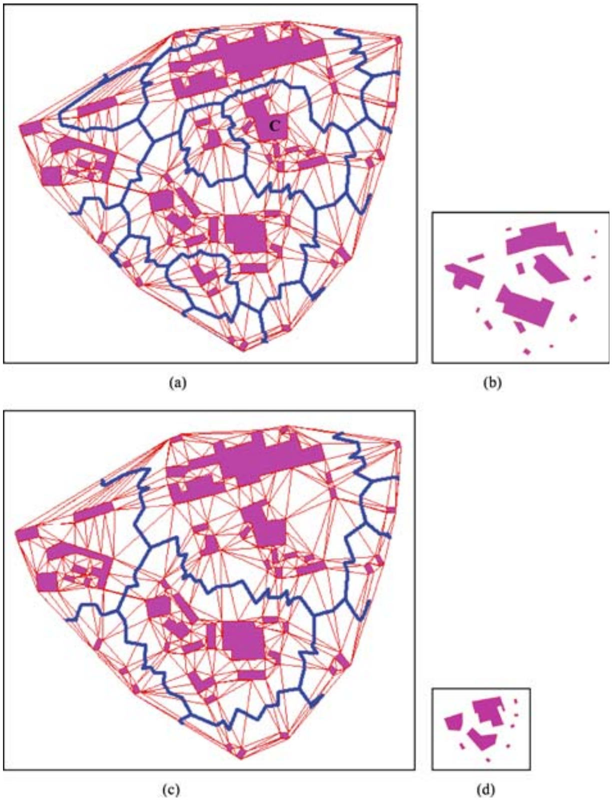


Fig. 8 Experiment 2 for building grouping and generalization (source map scale is 1:10,000): The buildings are complex-shaped but still basically orthogonal in the corners, and show different orientations and little parallelism. **a** Grouping result for generating 1:25,000 map. **b** Generalized map at scale 1:25,000. **c** Grouping result for generating 1:50,000 map. **d** Generalized result at scale 1:50,000. All maps not shown to scale

values between two objects are just above or below their corresponding threshold values (traditional cartographers may face similar dilemmas when having to make discrete decisions in the generalization process).

In our experiments, each group that is formed for the generalization to smaller scale maps is exactly a combination of several groups used for the generalization of larger scale maps, though each grouping process is performed using the same source data set (i.e. each grouping process starts from the 1:10,000 scale data). This can easily be seen by comparing Fig. 7a with Fig. 7c, Fig. 8a with Fig. 8c, and Fig. 9a with Fig. 9c respectively. This is a kind of ideal grouping, as such hierarchical structures between different scales are traditionally also generated in manual generalization. Furthermore, there is potential to exploit these hierarchies in other tasks related to generalization, such as the calculation of the density of buildings over certain areas of a map at different aggregation levels.

Matching between building groups to generalization operators and algorithms (i.e. the third research question formulated in the introduction) is a considerably hard problem. Our approach controls this process by means of a series of rules based on parameters such as the number of buildings, the area of buildings, the ratio between free space and sum area of buildings, etc. One of the operations not considered in the approach is map feature displacement. This could be applied as an optimization or post-processing step of the generalized results [1], [17]. In our work, conflicts are settled simply by slightly moving overlapping buildings or reducing their size. It is clear that more effort could be spent on addressing the third research question, that is, the matching of generalization operators to

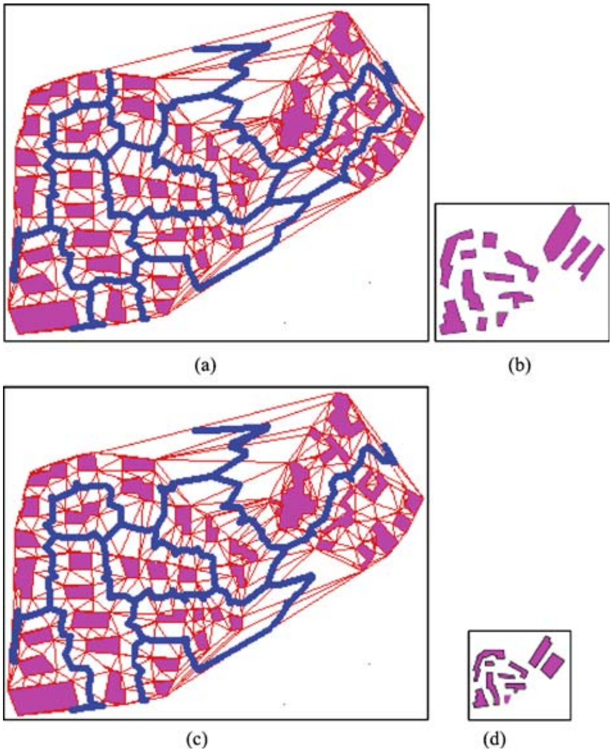


Fig. 9 Experiment 3 for building grouping and generalization (source map scale is 1:10,000): The buildings have complex and non-convex shapes with arbitrary angles in the corners, and have arbitrary orientations and little parallelism. **a** Grouping result for generating 1:25,000 map. **b** Generalized map at scale 1:25,000. **c** Grouping result for generating 1:50,000 map. **d** Generalized result at scale 1:50,000. All maps not shown to scale. BDTopo data courtesy of Institut Géographique National (IGN), France

the characteristics of building groups. In the work presented here, however, we chose to focus primarily on the issue of building grouping, expressed by the two initial research questions posed in Section 1. Based on the building groups generated by our approach other, potentially better generalization algorithms could be used. Given the many parameters that are generated as a result of our approach, generalization algorithms will be well informed.

Finally, as the varied complexity and characteristics of the three test data sets seem to indicate, this approach has good adaptability in grouping and generalizing different types of buildings. It can be used to group and generalize buildings ranging from simple, rectangular shapes and regular arrangements, to non-convex, complex shapes in arbitrary directions and arrangements (cf. Figs. 7, 8 and 9).

7 Conclusions

This paper proposed an approach to automated building grouping and generalization. Three research questions mentioned in the introductory section were addressed and solutions proposed.

The first research question addressed the issue of achieving a quantitative description of relations and patterns of buildings. For this purpose six parameters corresponding to three Gestalt principles, i.e. proximity, similarity and common direction, are selected. For proximity, these are the parameters minimum distance and area of visible scope; for similarity, these are the area ratio and edge number ratio; and for common direction, smallest minimum bounding rectangle (SMBR) and direction Voronoi diagram (DVD) are used.

The second research question dealt with building grouping. Here, we used Delaunay triangulation to detect topological adjacency relations of buildings and generated 2-building groups firstly, and then constructed larger, intermediate groups according to a set of rules. After aggregation and separation of intermediate groups owning common buildings, final groups were created which can be used as a basis for generalization.

Finally, the third question focused on matching the characteristics of the building groups generated in the previous steps to appropriate generalization operations and algorithms. A series of rules based on parameters such as the number of buildings involved, the size of buildings, the ratio of building area and free space, etc. as well as threshold values such as a separation threshold and an area threshold, were established to perform this complex task.

The approach presented in this paper has been implemented in C++ and runs fully automatically. Experiments were conducted with three test data sets from two countries, representing different characteristics in terms of building shapes and arrangements. These experiments indicate that our approach is indeed adaptable to different kinds of building data. Intuitively, the patterns and distributions of buildings on source maps can be preserved after generalization. The scale change in our experiments spans a factor of 2.5 and 5, respectively. Whether our approach can also be used for greater scale transitions needs further research, particularly in the area of the development of a more comprehensive and flexible set of generalization algorithms, which has not been the focus of this paper. We believe, however, that our procedure for building grouping, as well as the many parameters that are generated on the shape and distribution of buildings, will facilitate this task.

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